Laser stabilization for space applications

EX-5 laser development

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LISA metrology

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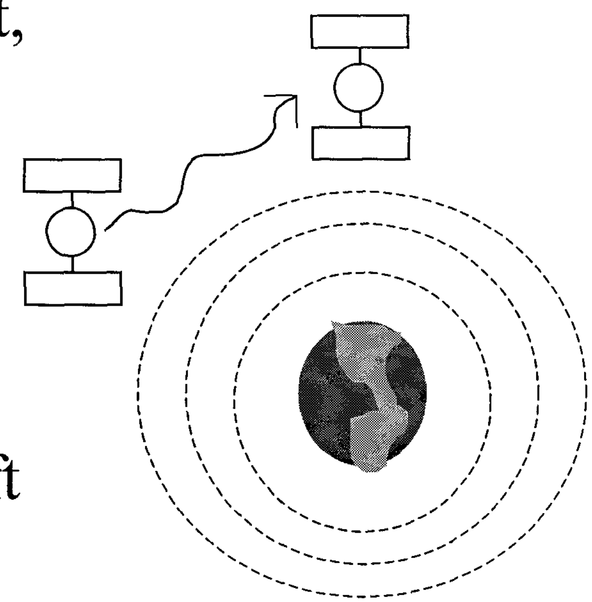
Relevance to ESE Missions

Laser stabilization is a mission-critical technology for the post-2002 Time-Dependent-Gravity Field Mapping Mission, EX-5 (+ LISA):

Optical metrology for gravitational mapping

Variations in mass distribution of the Earth puts a position-dependent acceleration on the spacecraft, causing a change in relative position.

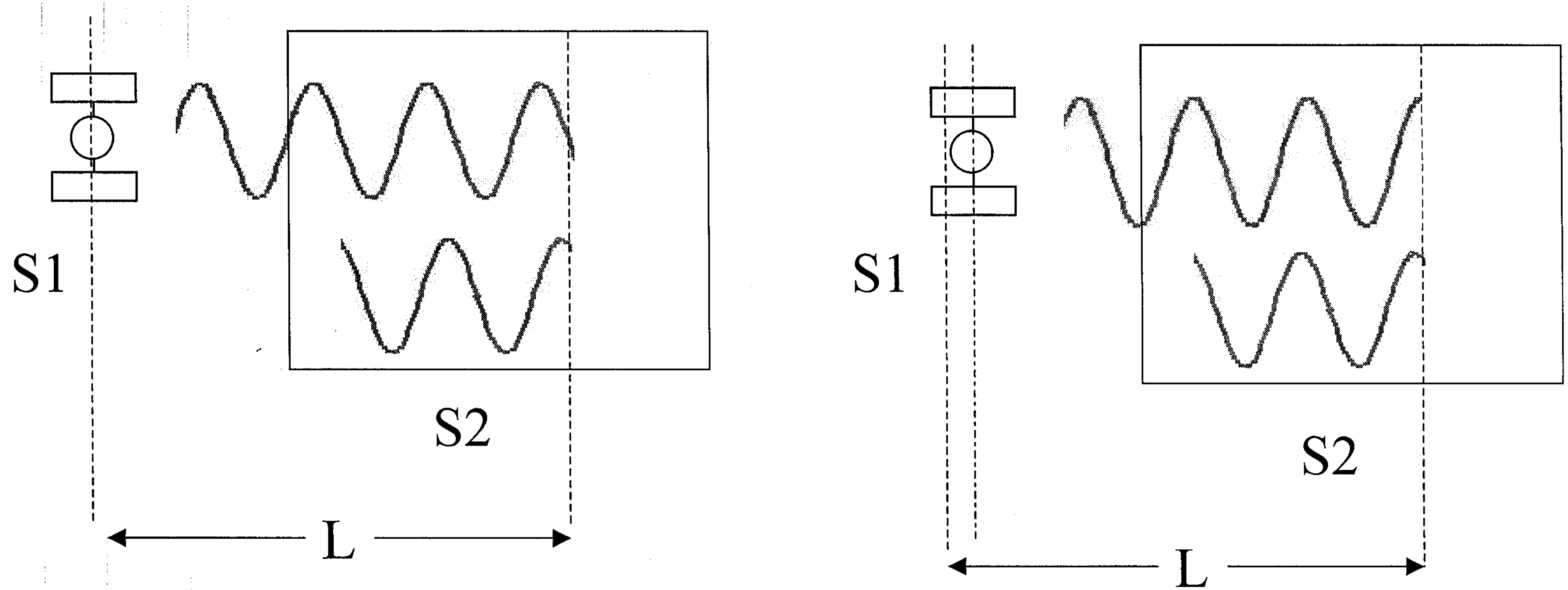


This distinct signature will change as mass distribution changes.

Micrometer-level resolution of relative spacecraft position gives information on mass (water) distribution (polar ice caps, large aquifers, ocean currents).

Metrology with Light

Comparing the phase of the incoming wave with the reference on S2 measures changes in the distance between the two satellites

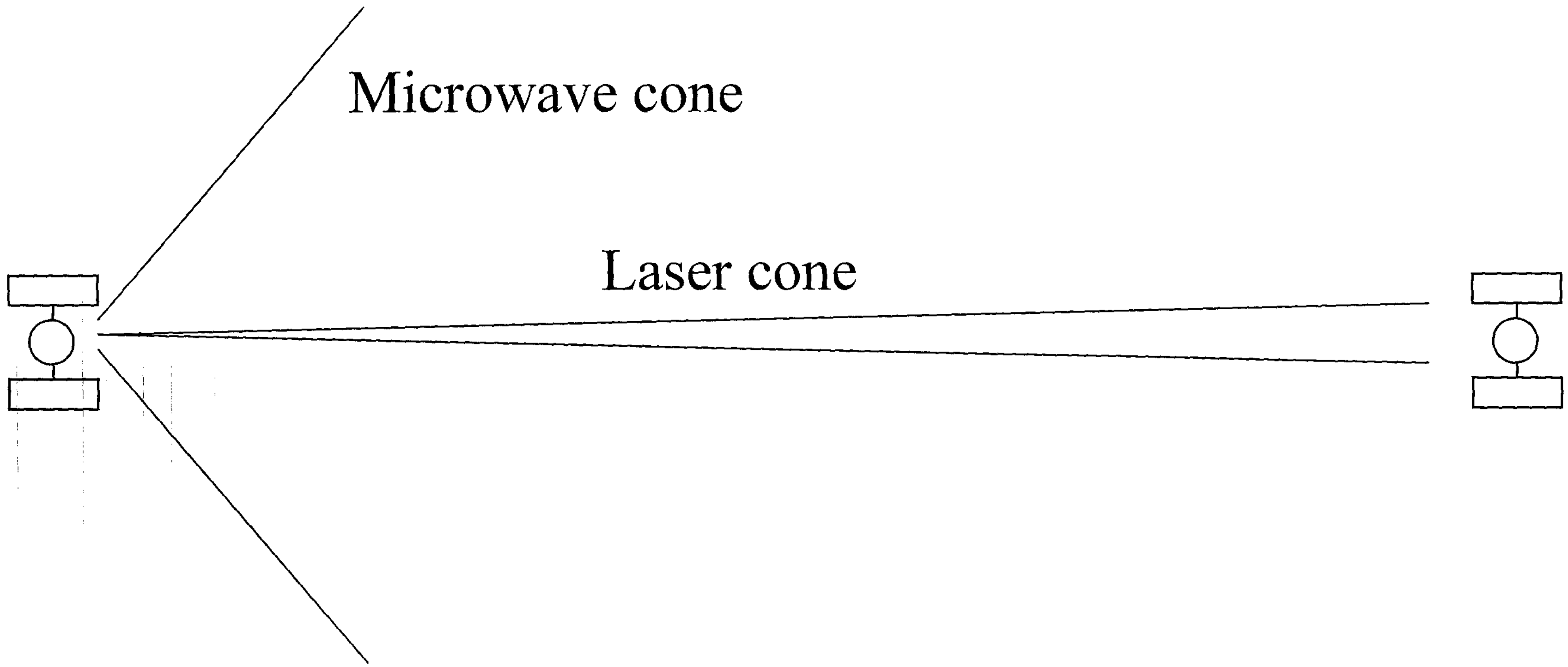


intersatellite distance L

inter-satellite distance L-$\lambda/4$

Fluctuations in the laser frequency limit the phase comparison

Benefits of Optical Frequencies

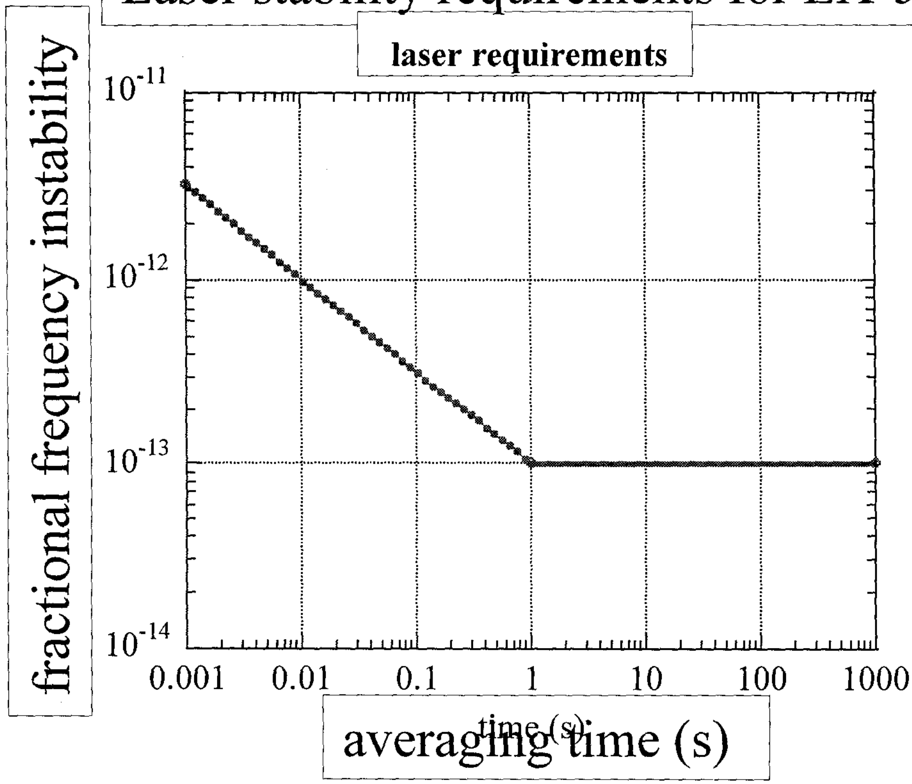


- no multi-path effects (directional)
- well-defined receiver
- direct ranging to test mass
- improved resolution (wavelength reduced by 10,000×)
- much better long-term stability (with atomic reference)

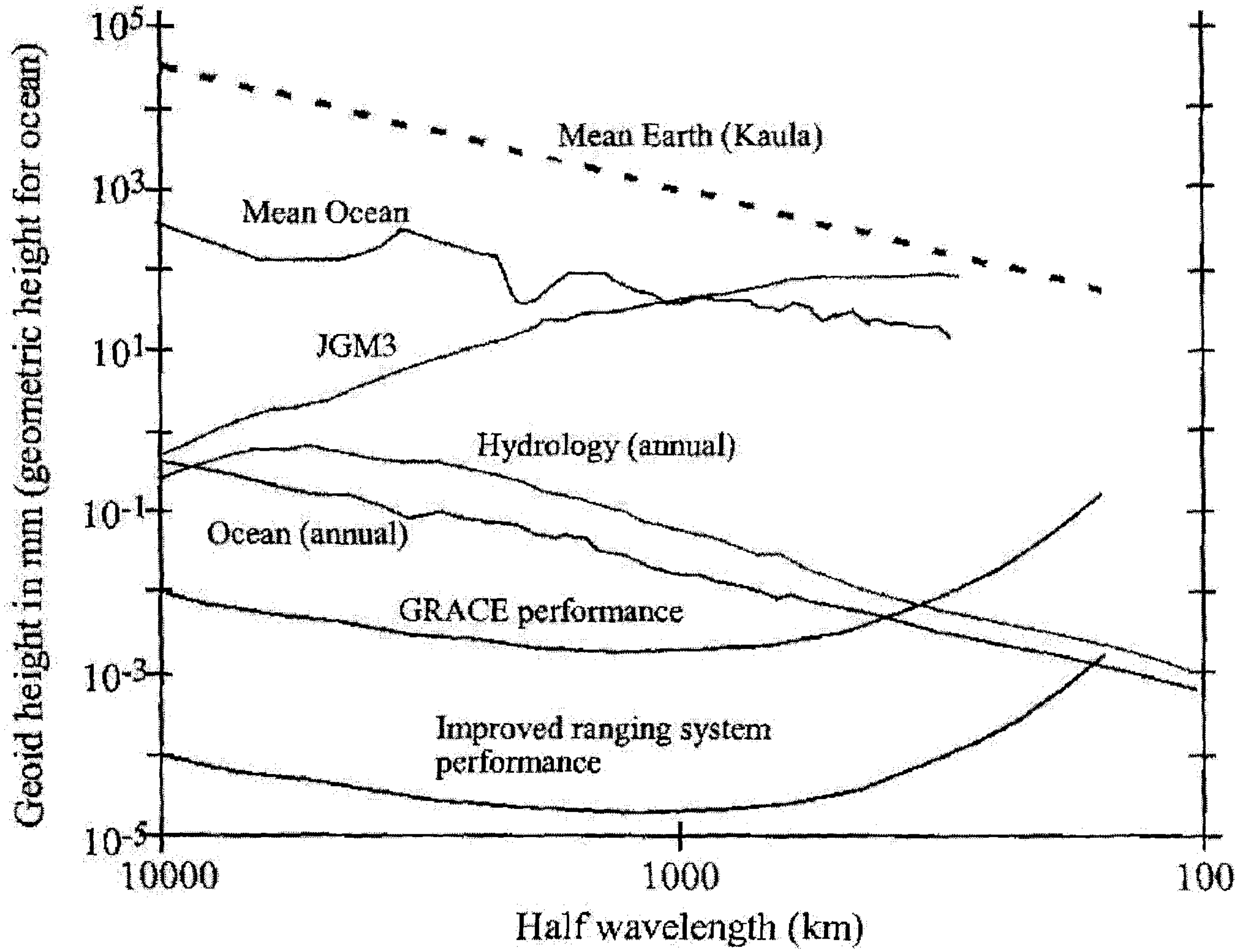
Task Objective

Develop a frequency-stabilized, high power (~100 mW) tunable laser system to support flight metrology, including GRACE 2 (EX-5) and LISA.

Laser stability requirements for EX-5



Sensitivity of GRACE and EX-5



From: M. Watkins, W. M. Folkner, S. Buchman, and B. Tapley, "EX-5: A laser interferometer follow-on to the GRACE Mission," GGG Conference (Banff, Canada, July 2000).

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NASA efforts toward laser stabilization

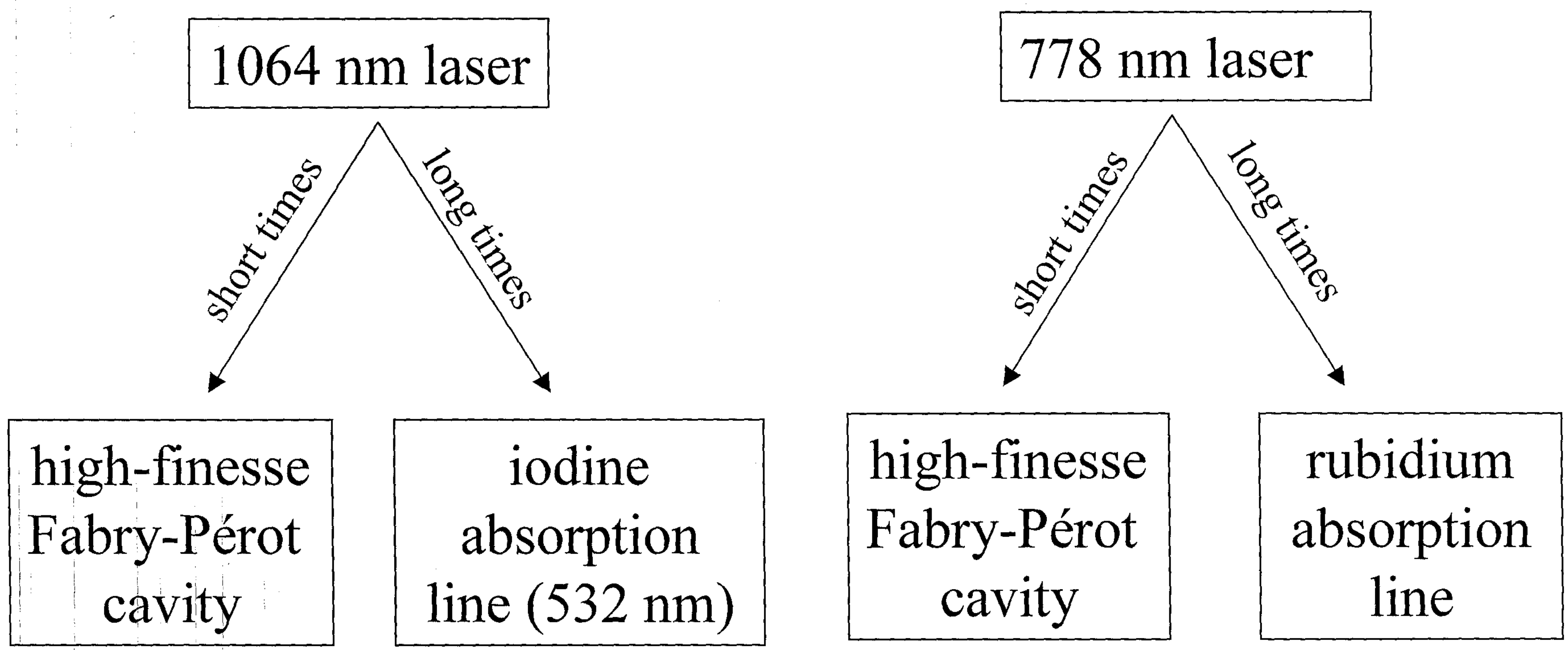
SUNLITE project:

Goal: Space-qualified, stabilized Nd:YAG laser for LISA, astrometry, optical communications, optical clocks, and fundamental physics

- NASA Langley, Stanford, NIST, JILA
- Thermal and mechanical modeling for cavity
- Optical bench design
- Space-qualifiable optical mounts and components
- Good short-term stability, but insufficient long-term stability ($\sim 10^{-11}$ at $\tau = 90$ min) for EX-5

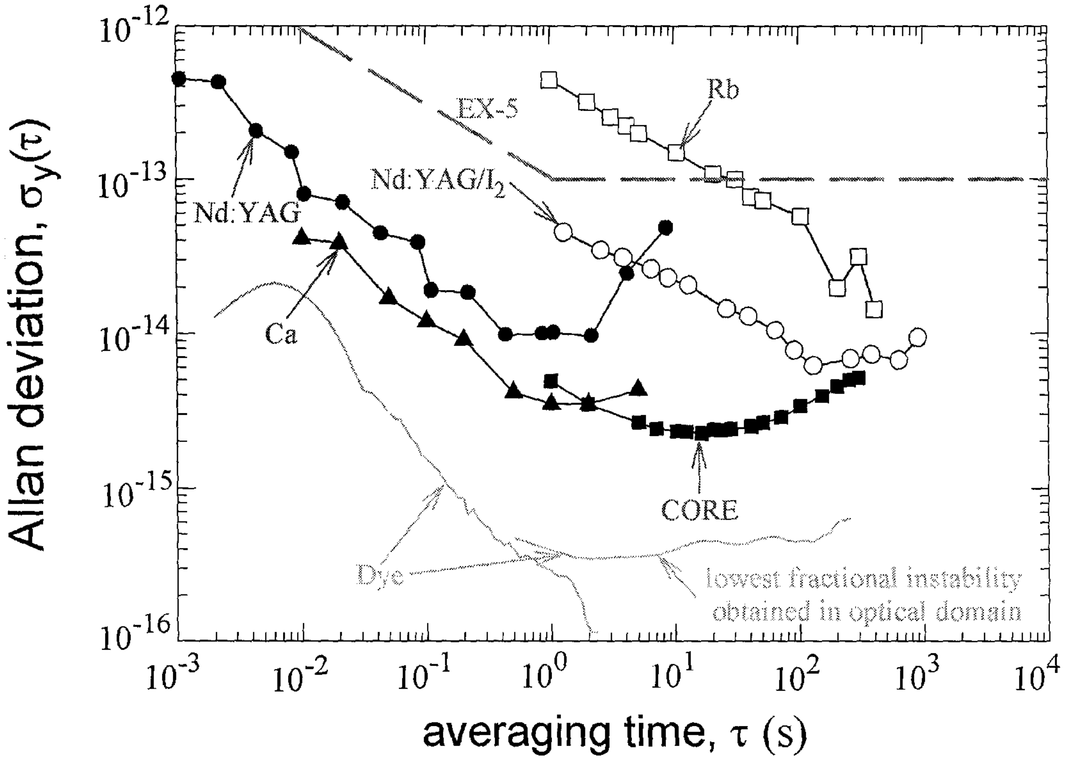
Project Overview: Approach

Parallel approaches to minimize risk, enhance output, and provide greater flexibility to candidate users.



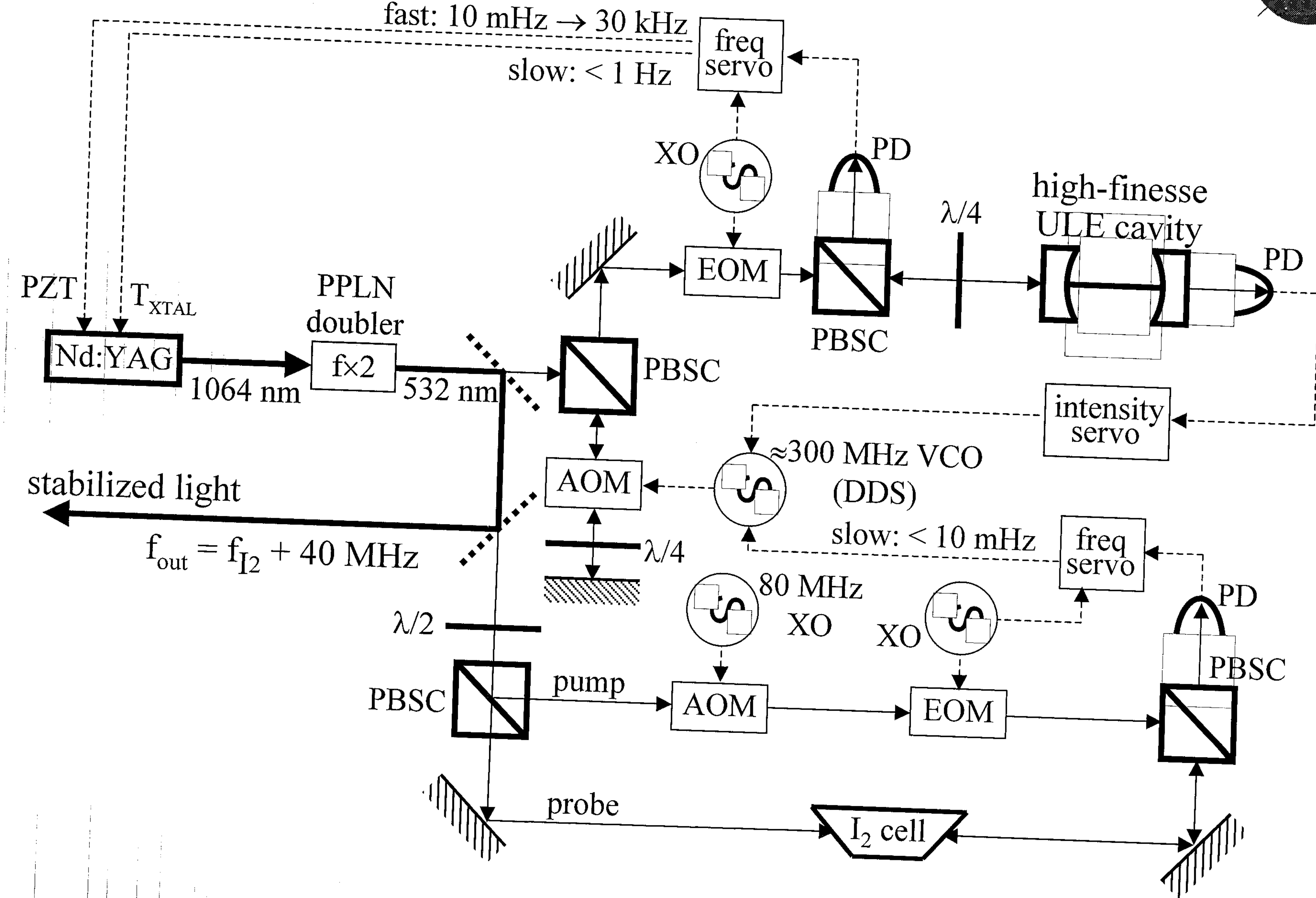
Performance of each system expected to surpass requirements

Fractional frequency instability of stabilized lasers

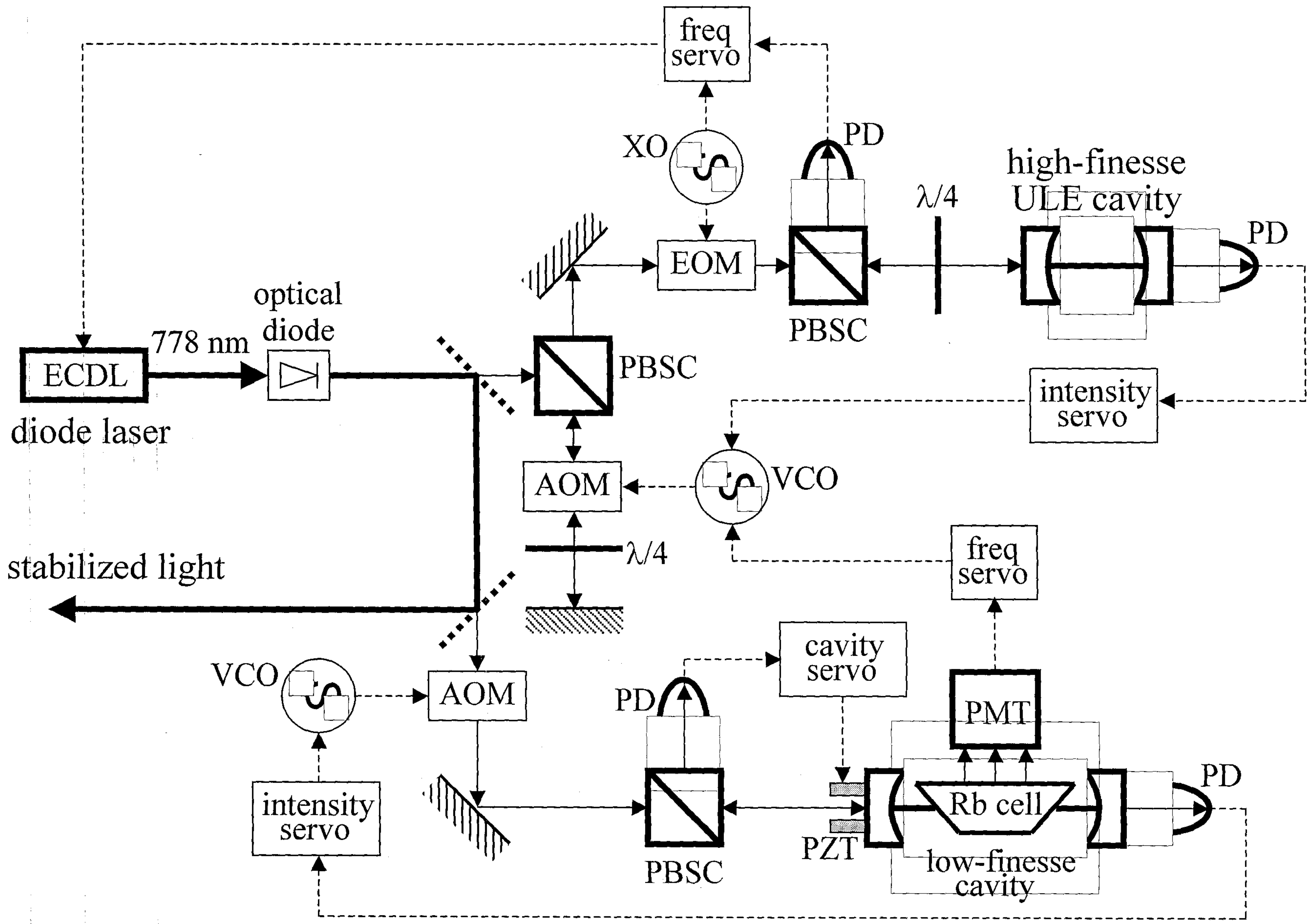


Nd:YAG ----- Sampas *et al.*, Opt. Lett. **18**, 947 (1993).
Nd:YAG/I_2 -- Hall *et al.*, IEEE Trans. Instrum. Meas. **48**, 583 (1999).
Rb ------------ Touahri *et al.*, Optics Comm. **133**, 471 (1997).
Ca ------------ Oates *et al.*, Opt. Lett. **25**, 1603 (2000).
CORE -------- Seel *et al.*, Phys. Rev. Lett. **78**, 4741 (1997).
Dye ----------- Young *et al.*, Phys. Rev. Lett. 82, 3799 (1999).
EX-5 ---------- EX-5 requirement

Stabilization to I_2 transition at 532 nm



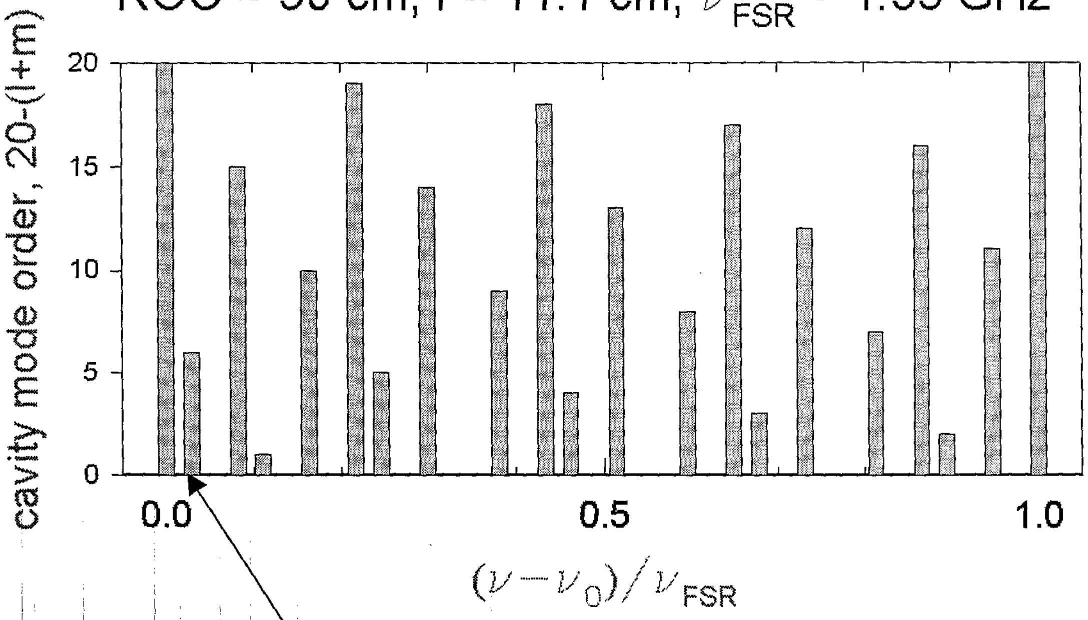
Stabilization to Rb two-photon transition at 778 nm

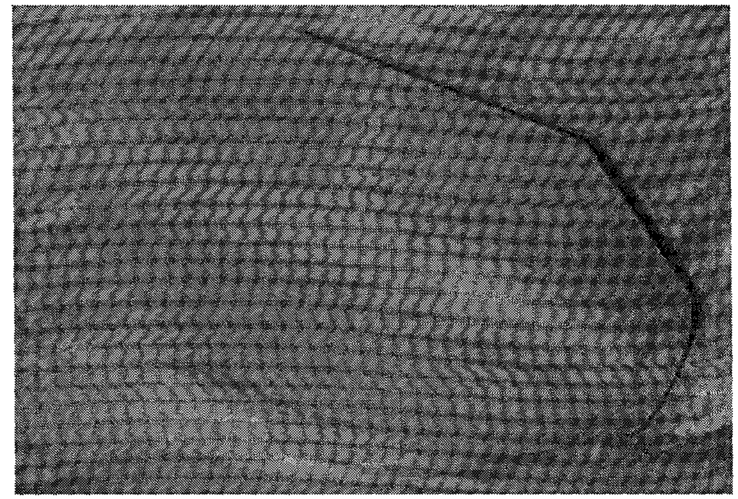


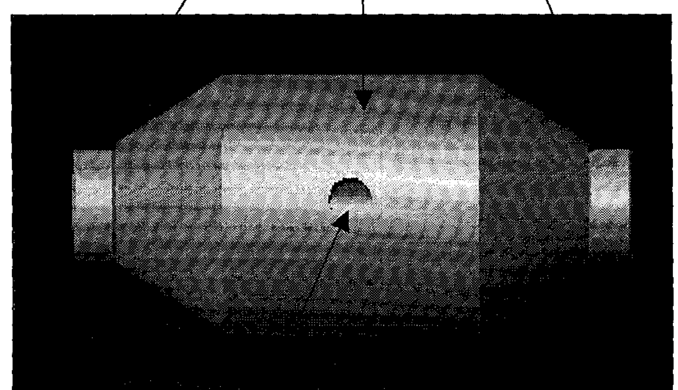
Design of Fabry-Pérot cavity

TEM$_{lm}$ mode frequencies in Fabry-Perot cavity

ROC = 50 cm, l = 11.1 cm, ν_{FSR} = 1.35 GHz

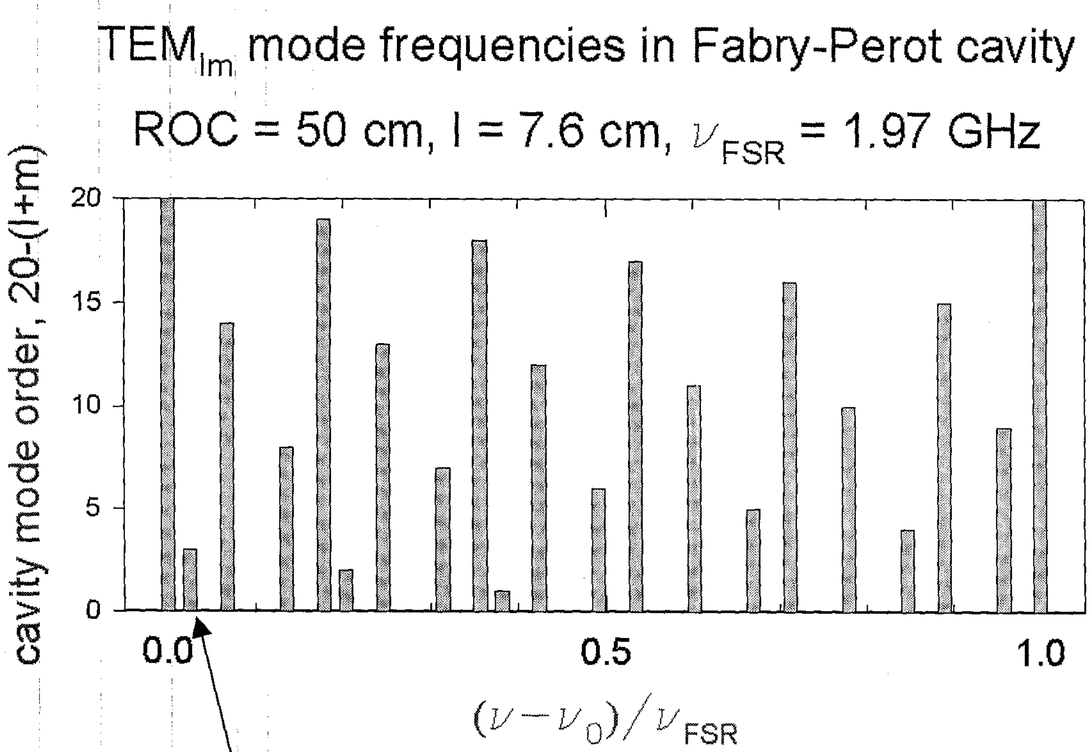


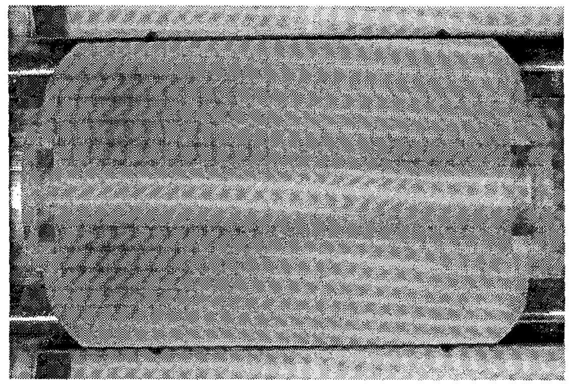


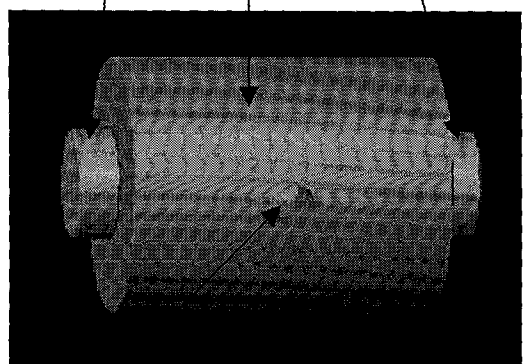


- l+m=14 mode is 39 MHz from TEM$_{00}$ mode
- Cavity shape yields good stiffness/mass ratio
- Longer cavity gives higher Q, but uses lower grade of ULE

Design of Fabry-Pérot cavity



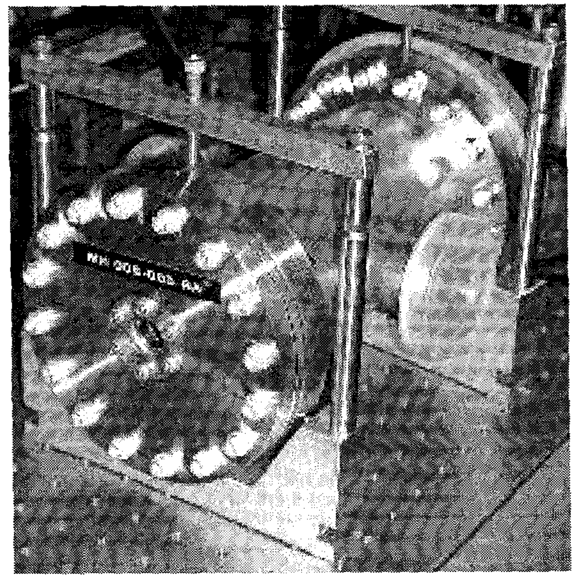


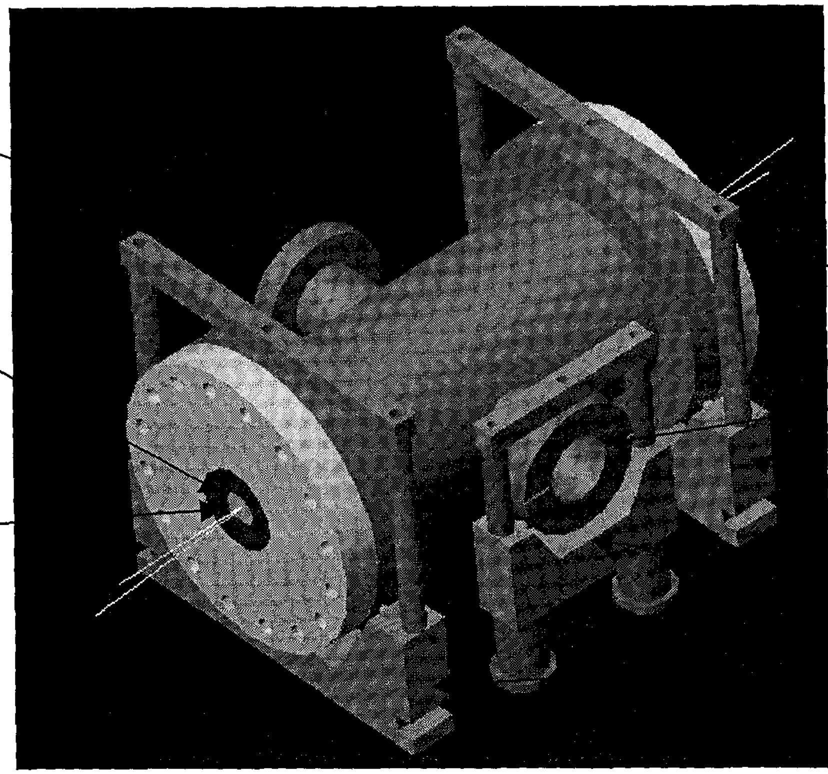


- l+m=17 mode is 49 MHz from TEM$_{00}$ mode
- Shorter cavity has lower Q, but made from higher grade of ULE

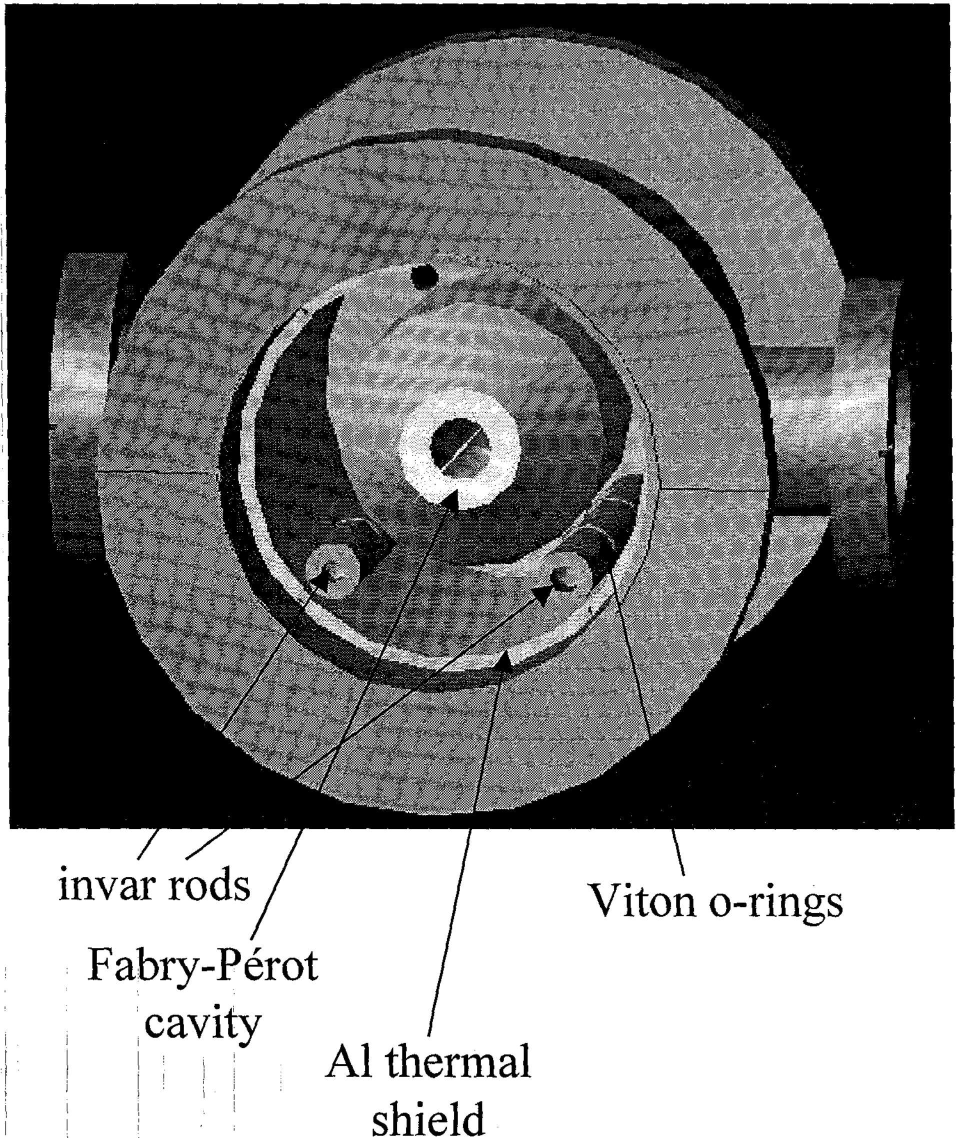
Vacuum chamber for Fabry-Pérot cavity

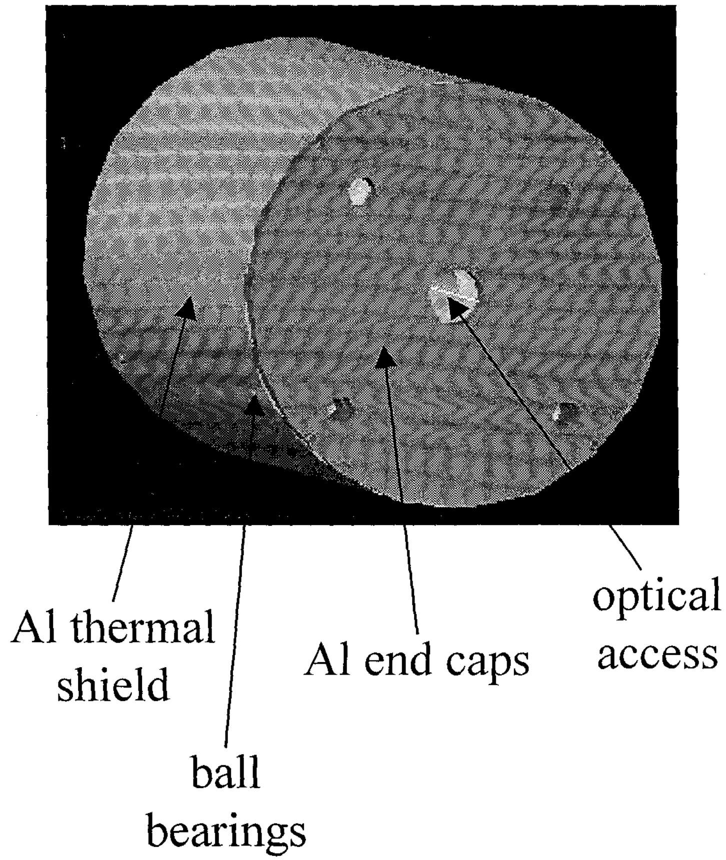
- Parts procured for 4 vacuum systems
- 2 chambers assembled for 532 nm and 778 nm





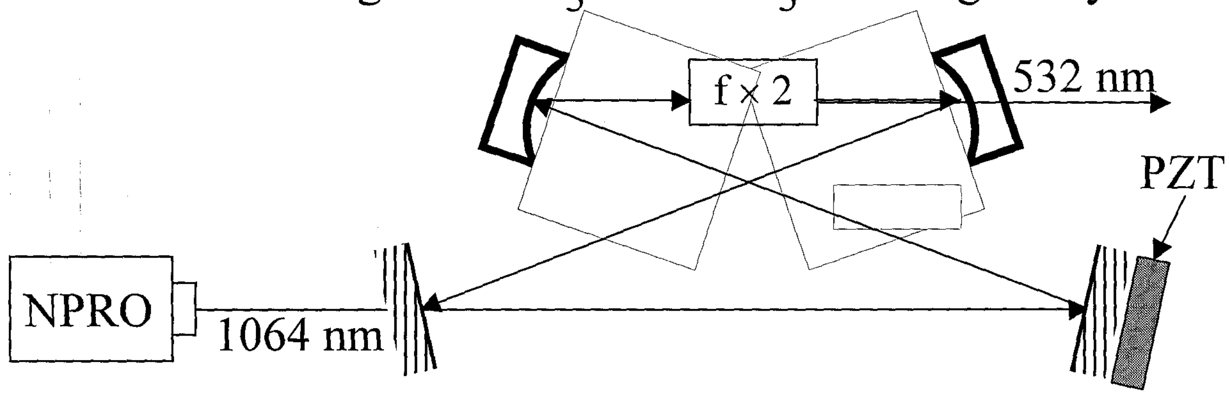
Thermal shield for Fabry-Pérot cavity



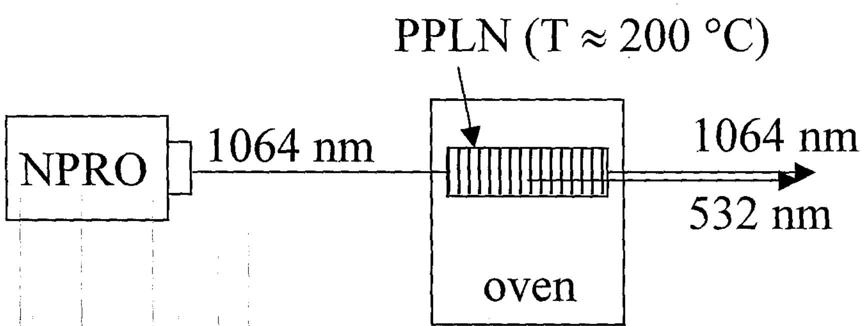


Frequency Doubling

The Nd:YAG laser puts out 1064 nm light, which must be frequency doubled to 532 nm in a nonlinear crystal to compare to iodine absorption lines



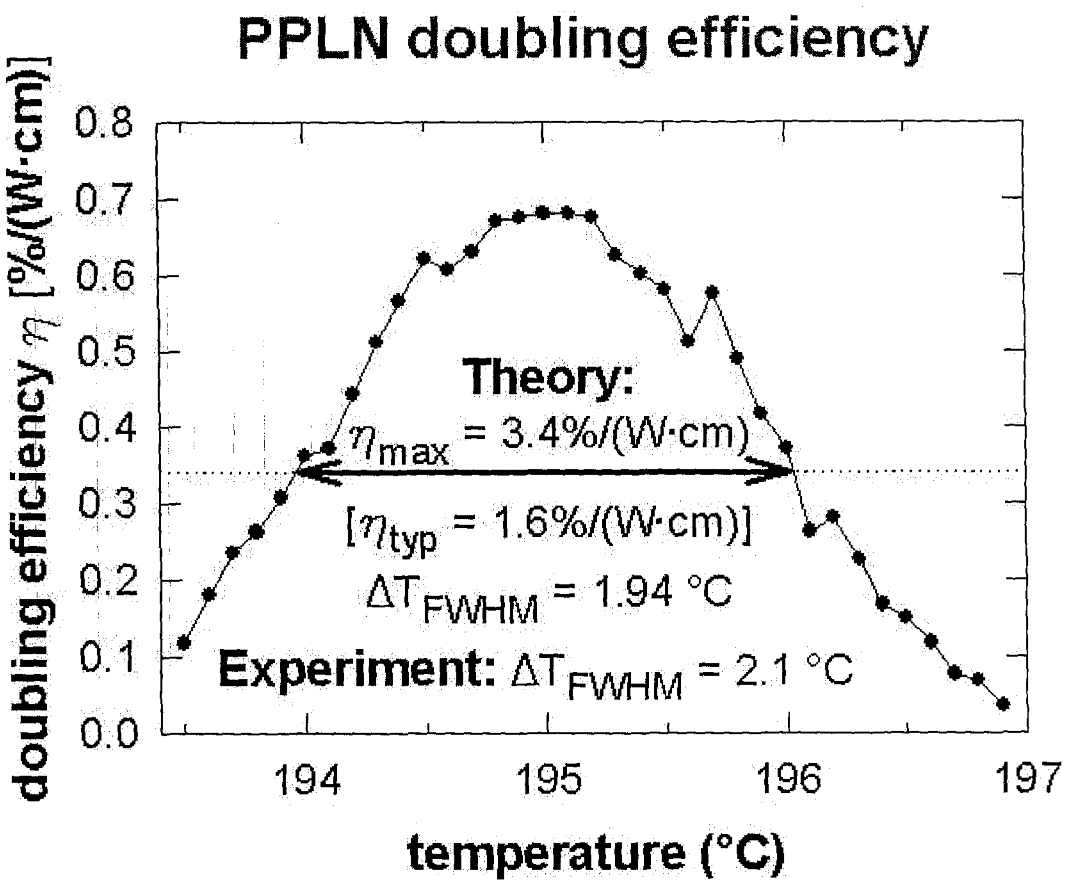
Single-pass PPLN doubler

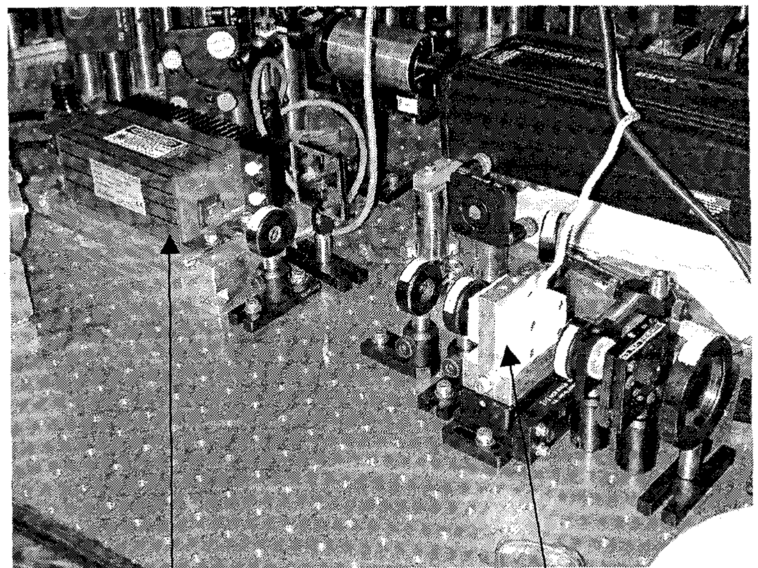


PPLN advantages

- 20× the single-pass power of LiNbO$_3$
- 2× the single-pass power of KNbO$_3$, with 1/4 the temperature sensitivity and 1/40 the angle sensitivity

Frequency Doubling



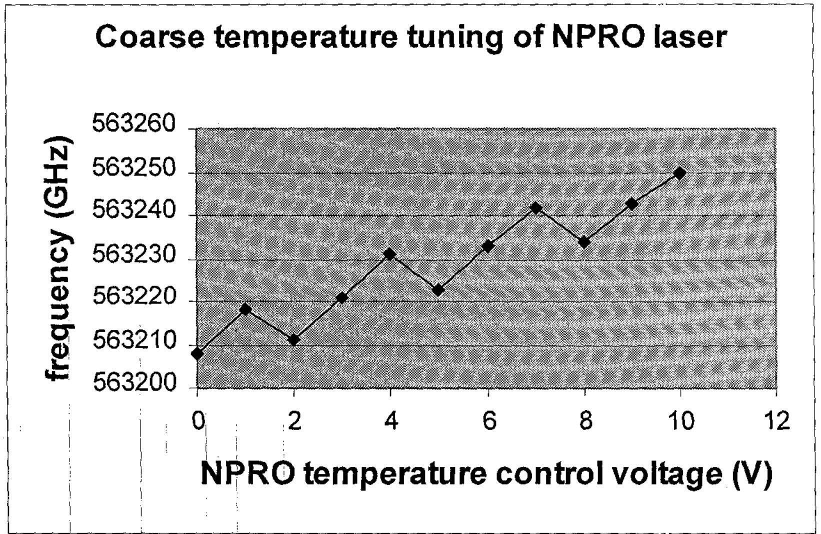


NPRO laser (500 mW @ 1064 nm)

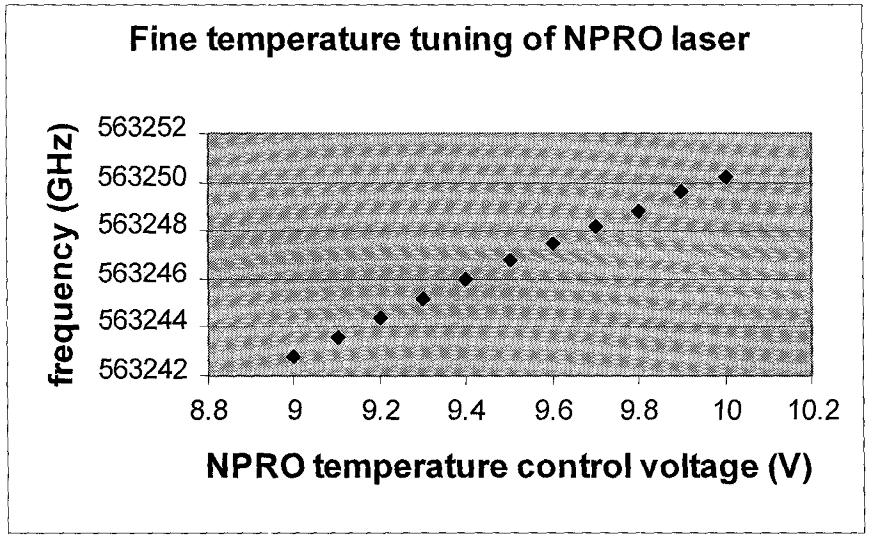
PPLN oven

Nd:YAG Laser Tuning

Tuning characteristics of Nd:YAG laser with crystal temperature



Coarse tuning: 3.8 GHz/V (at 532 nm)



Fine tuning: 7.4 GHz/V (at 532 nm)

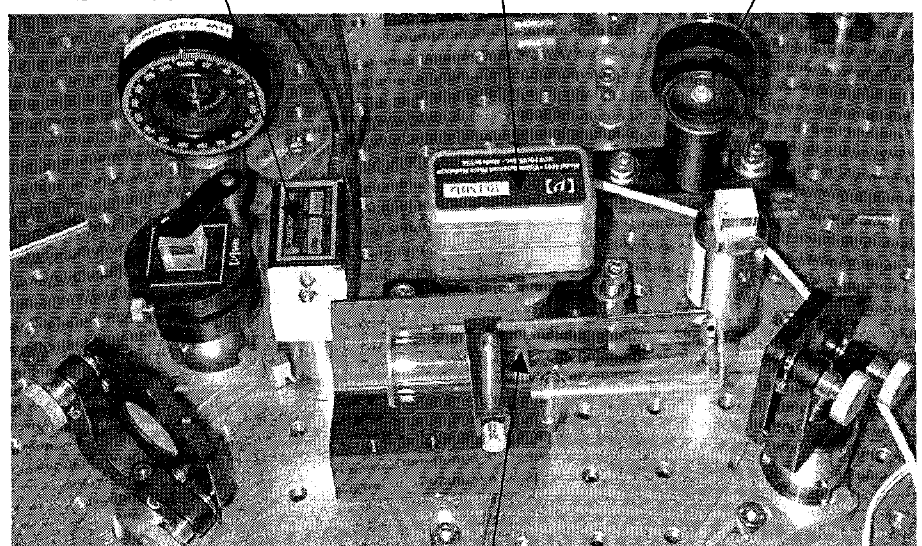
Iodine Spectroscopy

First fluorescence signal at 532 nm

Iodine absorption lines observed so far (Doppler only):

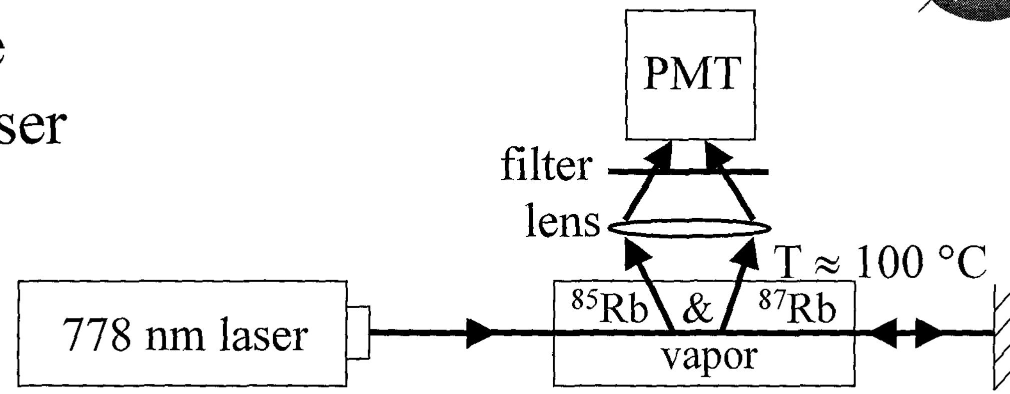
1104:a_1 R(57)32-0
1105:a_1 P(54)32-0
1106:a_1 P(119)35-0
1109:a_{21} P(83)33-0

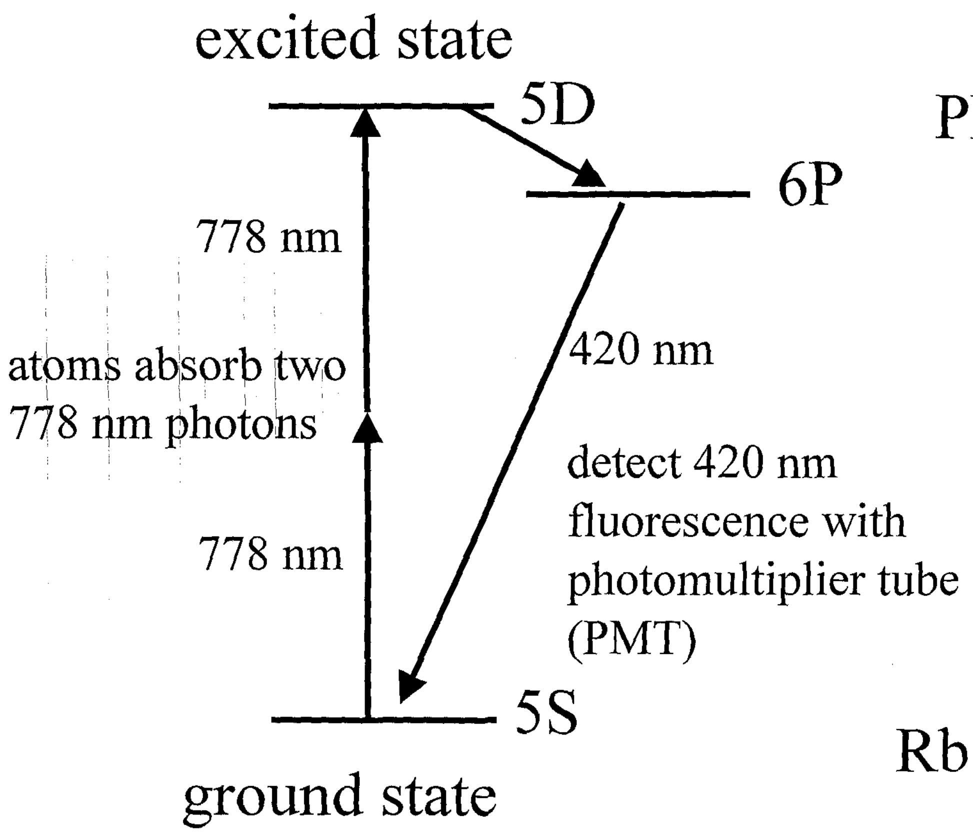
Doppler-free spectroscopy set up

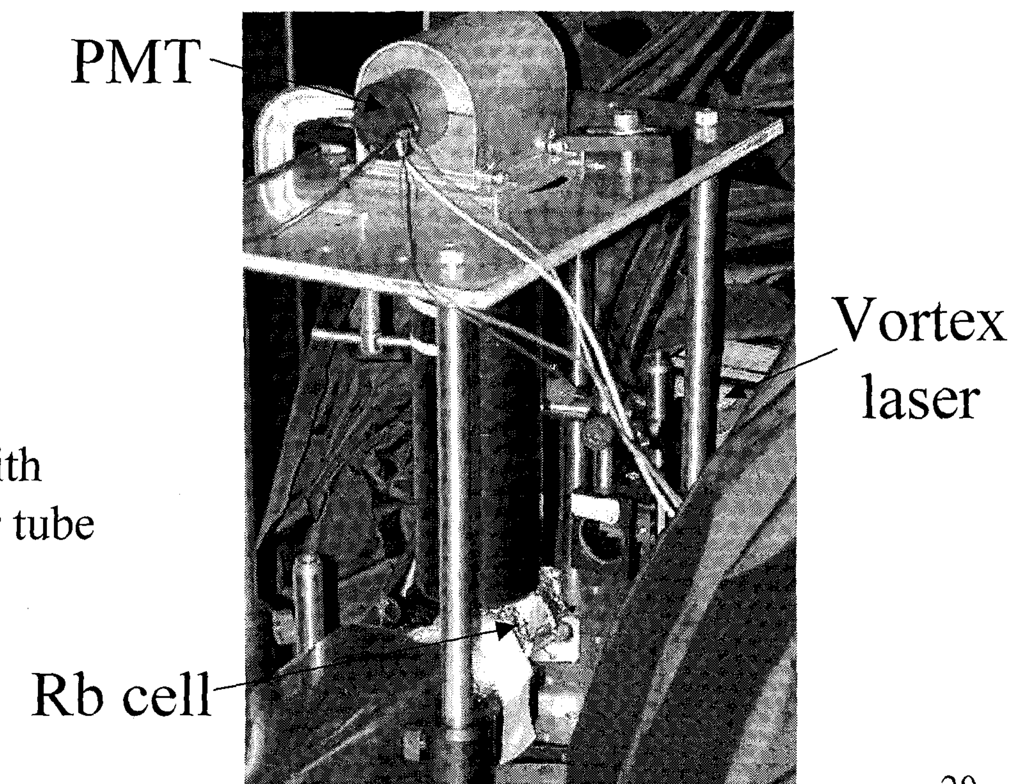


Rubidium 2-photon transition

Rb atoms serve as an absolute frequency reference for the laser







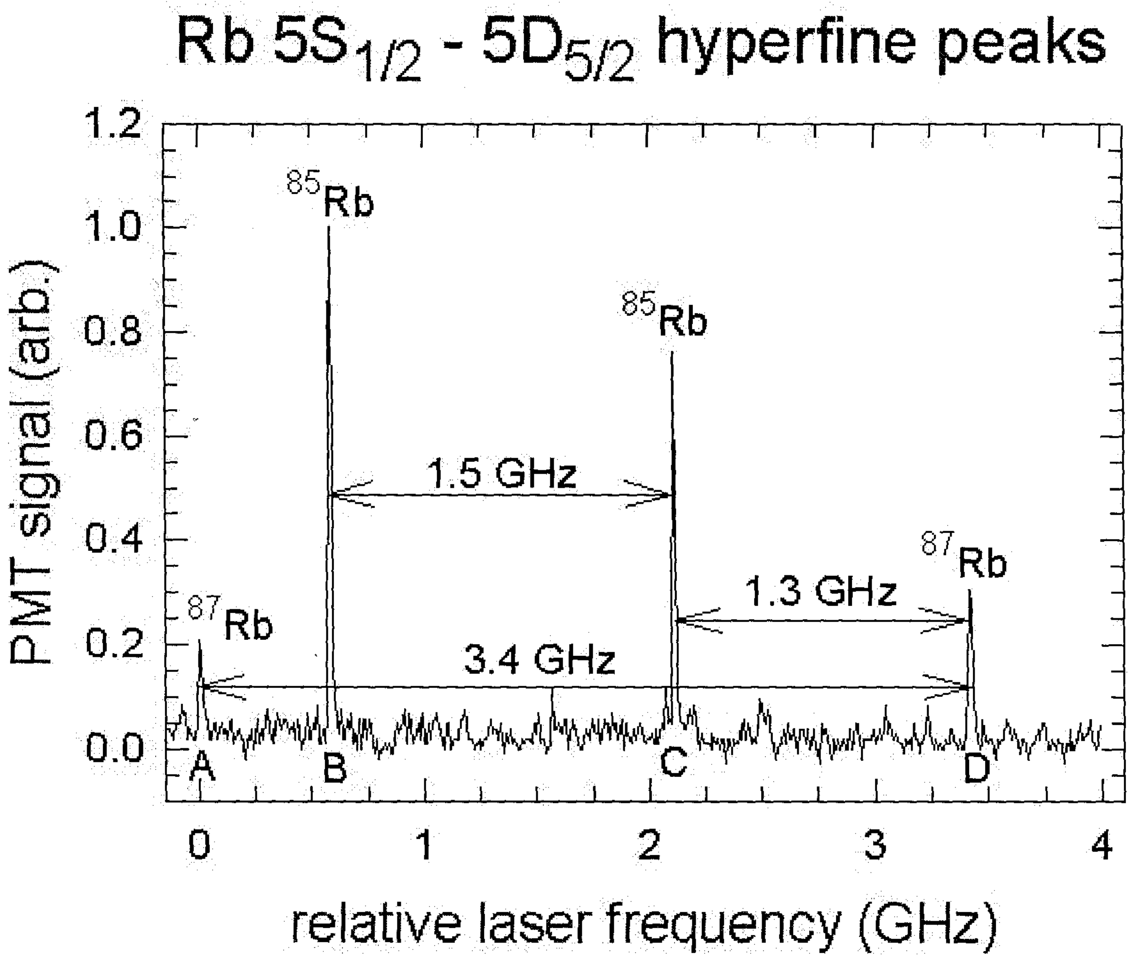
^{85}Rb & ^{87}Rb $5S_{1/2}$-$5D_{5/2}$ Transitions

Peak A is at 778. 108 nm

Peak B is at 778.107nm

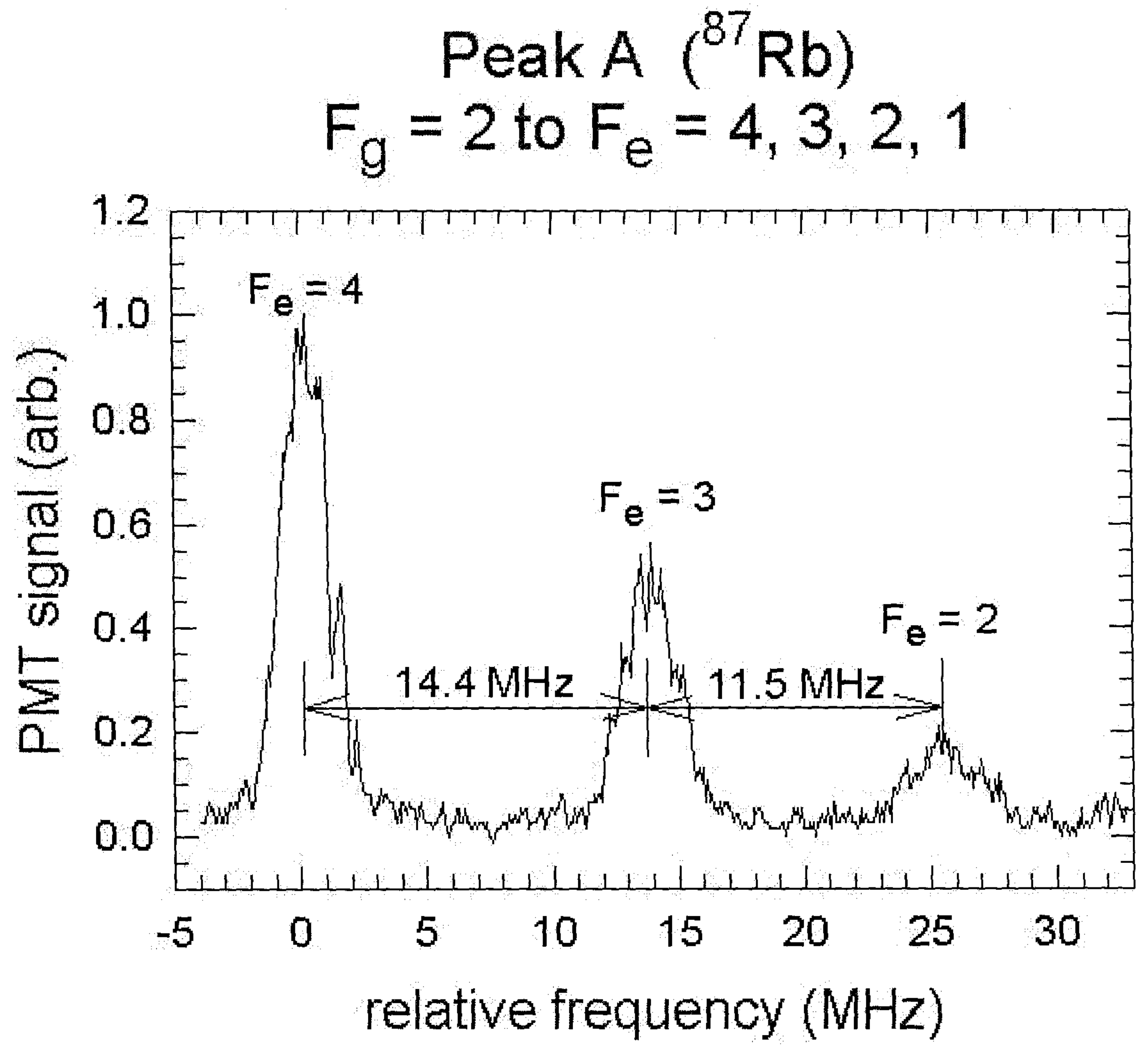
Peak C is at 778.103 nm

Peak D is at 778.100 nm



Measured with a Burleigh WA100 wavemeter

Hyperfine components of Peak A



Transition linewidth consistent with laser frequency noise

Frequency identifications from F. Nez *et al.*, Opt. Commun. **102**, 432 (1993).

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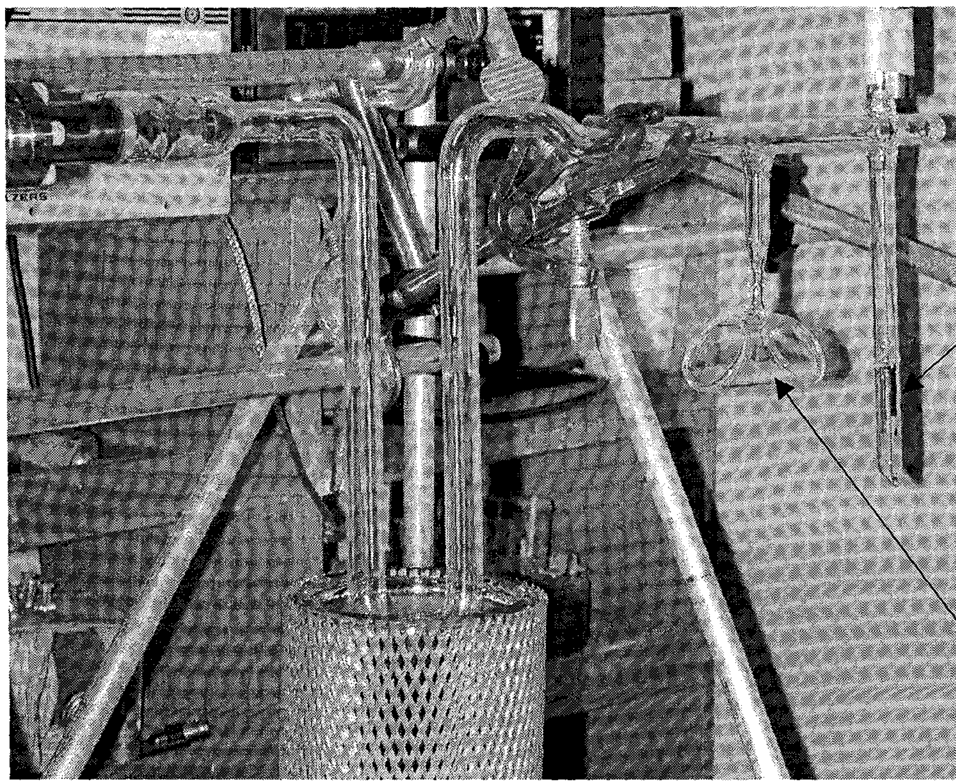
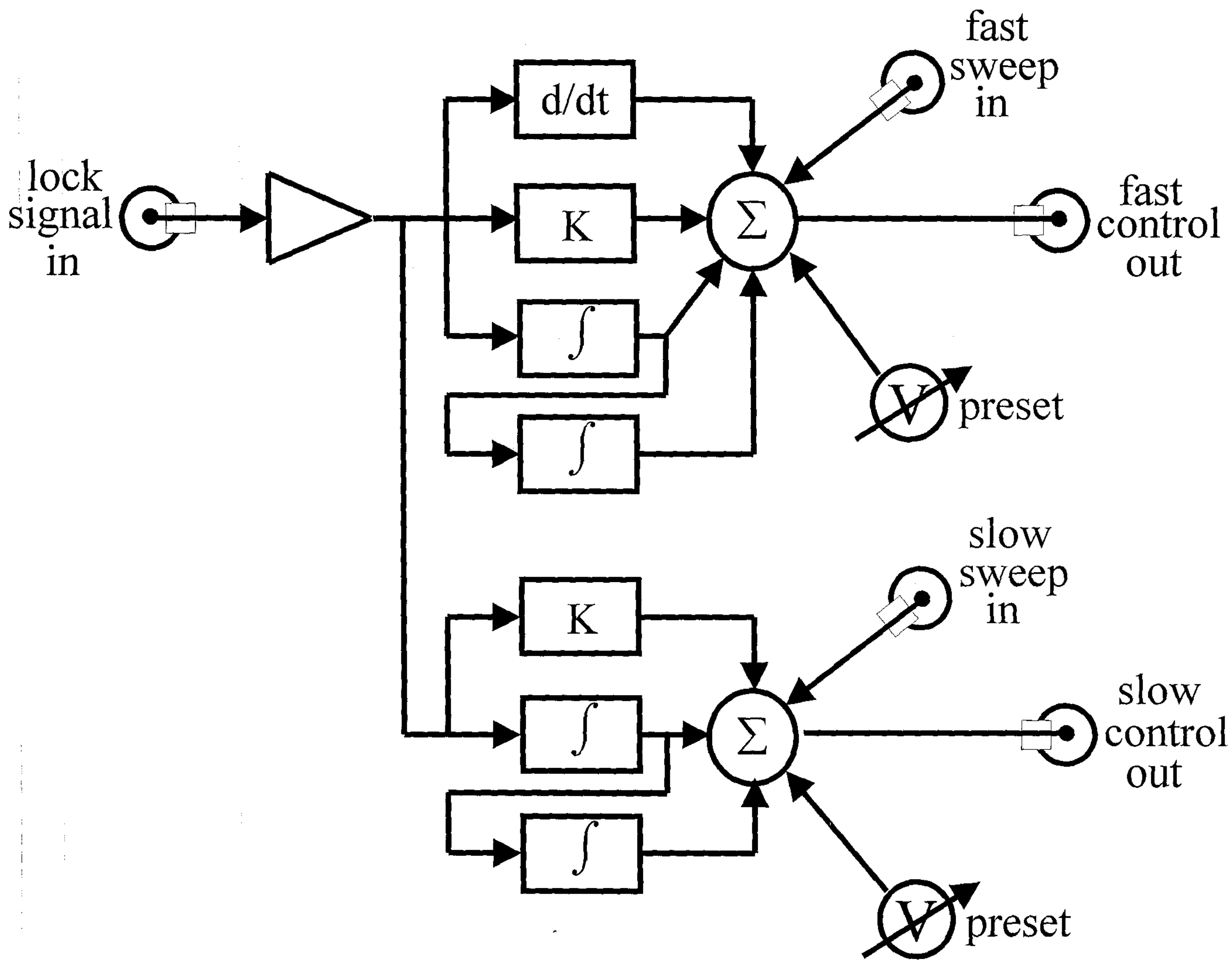
Reference Cell Prototyping

We are beginning vapor cell prototyping in our laboratory to test some of our design concepts.



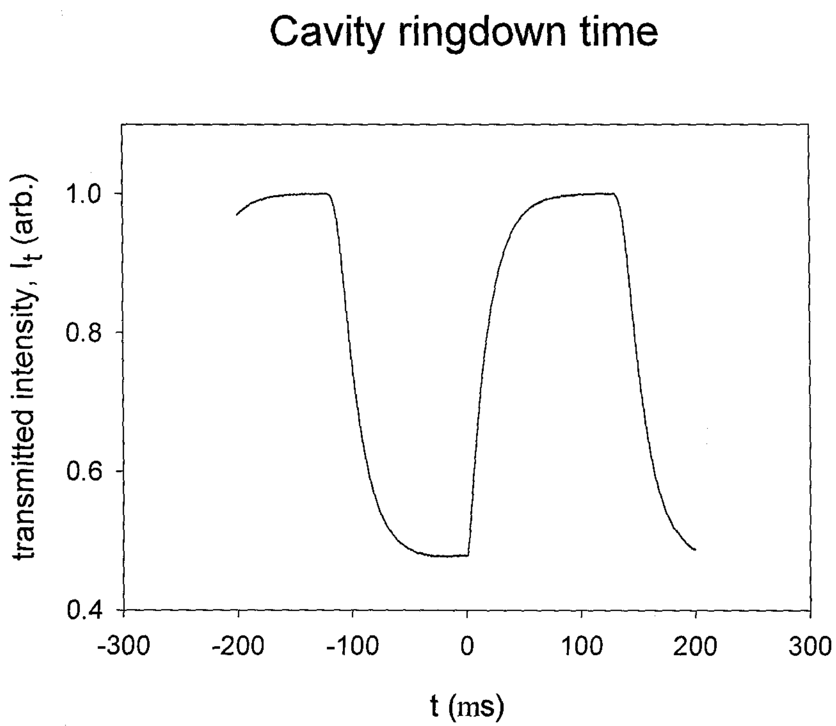
Laser lock electronics design
Block diagram



Finesse of Fabry-Pérot cavities

Measure ring-down time for cavities with 532 nm mirrors:

Cavity # 1: $\tau = 18\ \mu s \Rightarrow F = 150{,}000,\ \Delta\nu = 8.8$ kHz



Evaluation of bonding techniques for the LISA optical bench

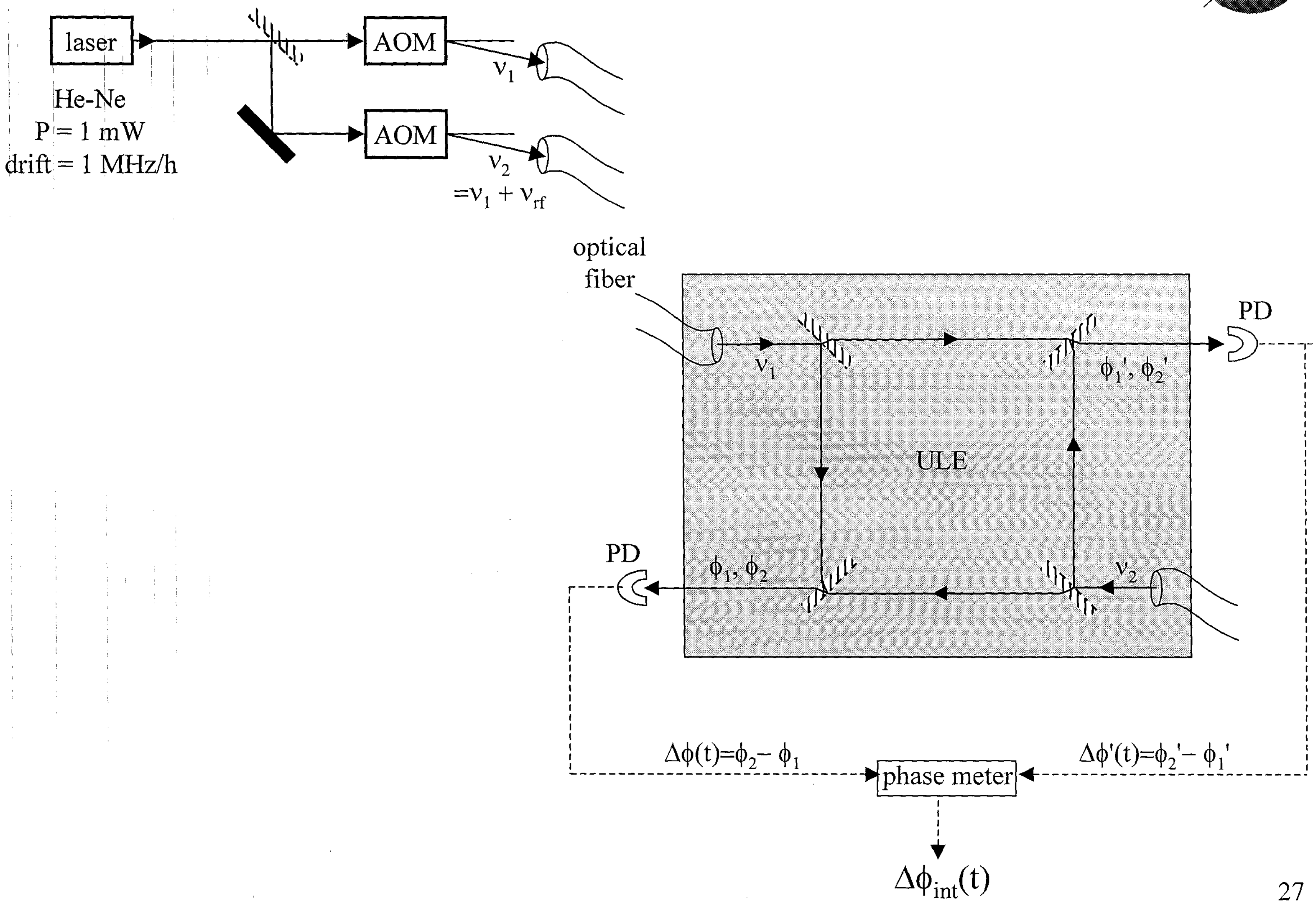
Goal:

Test bonding techniques of optics onto a ULE platform with a resolution in position instability < 10 pm/Hz$^{1/2}$ at frequencies from 1 Hz to 10^{-3} Hz.

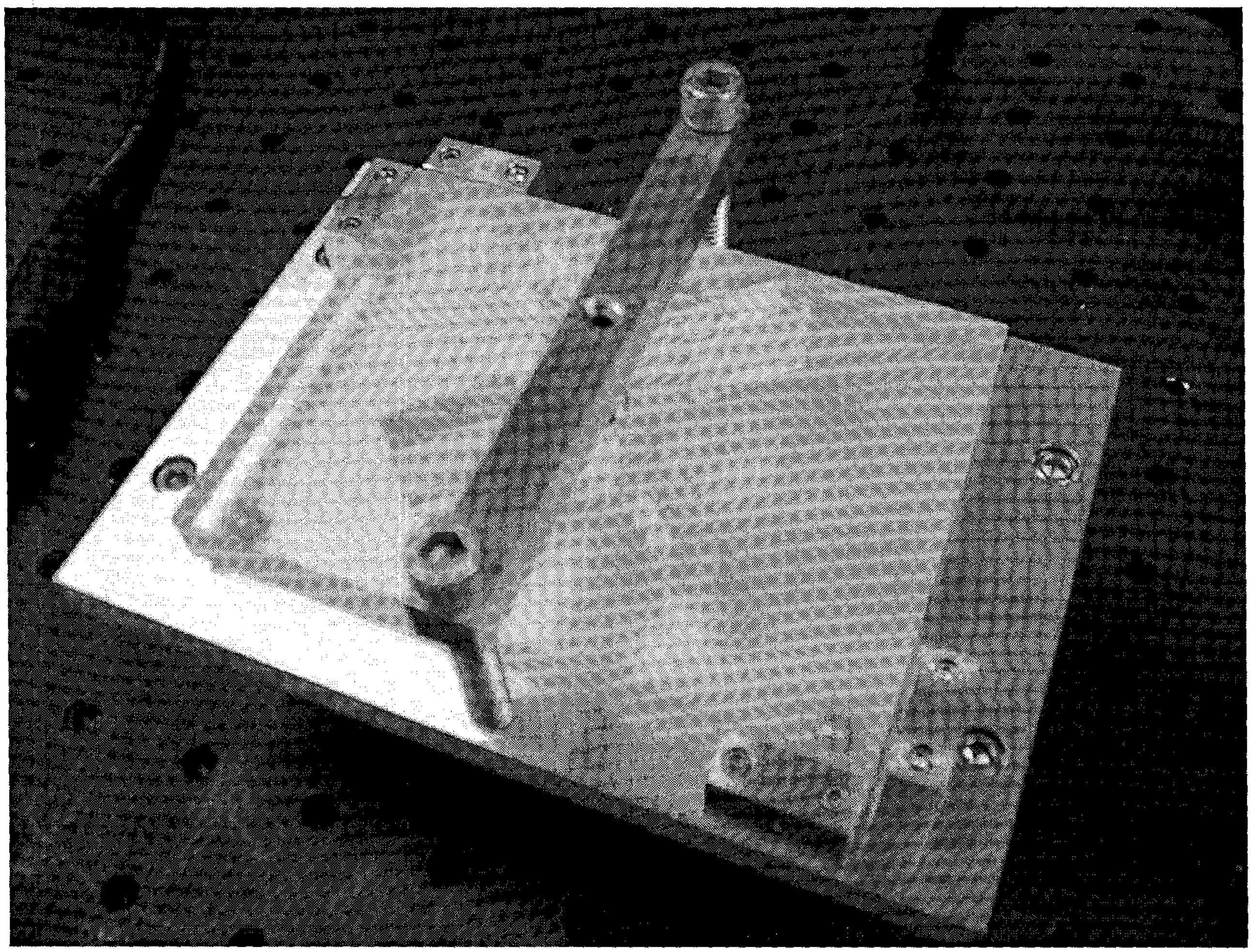
Method:

Measure relative motion of the optics using interferometric techniques and a precision phase measurement system.

Interferometer Design

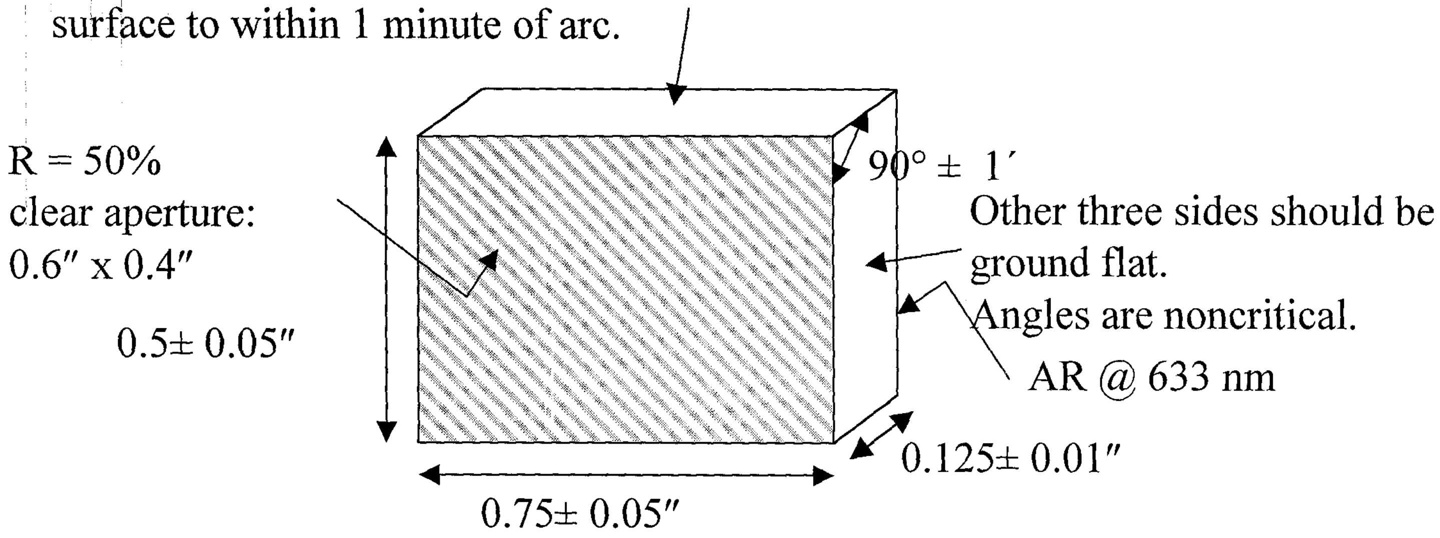


Interferometer with nonpolarizing optics

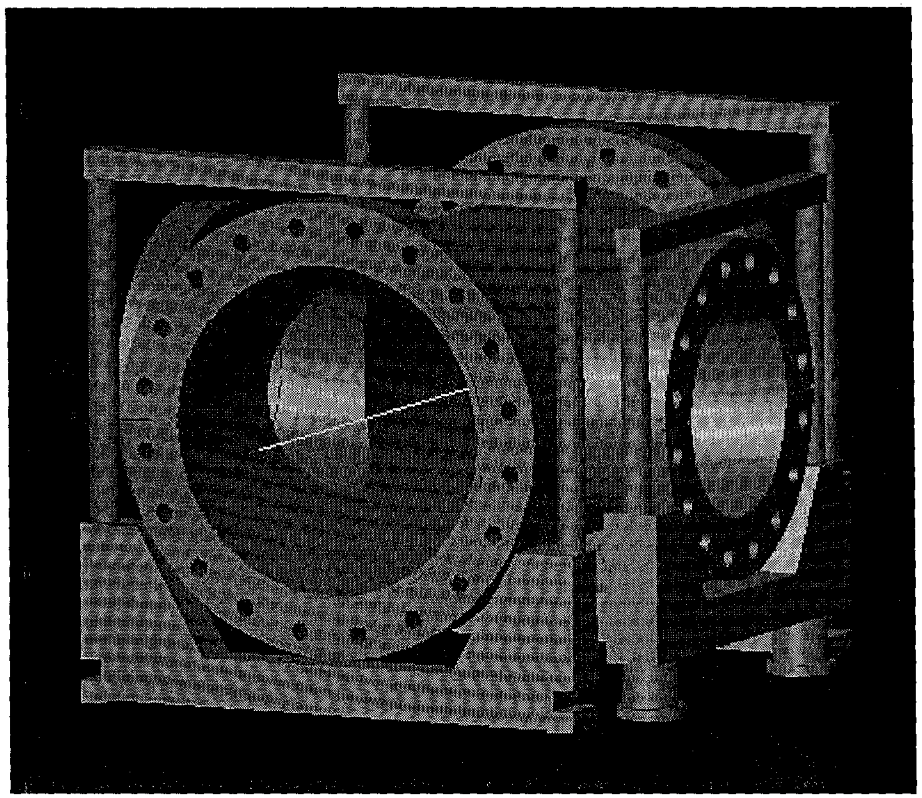


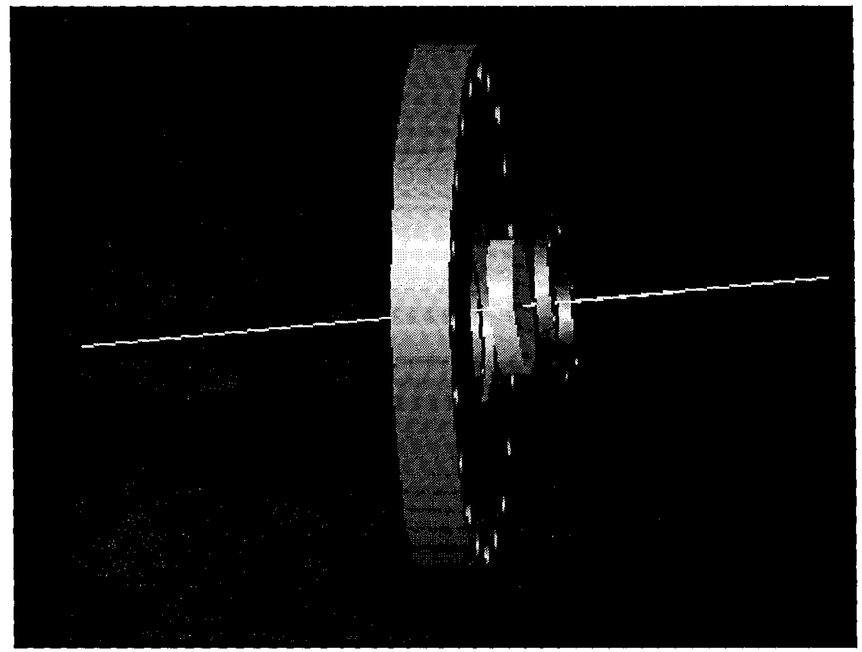
Beamsplitter specifications

One long side should be ground and polished to λ/4 at 633 nm. This polished edge should be normal to the 50% reflecting surface to within 1 minute of arc.

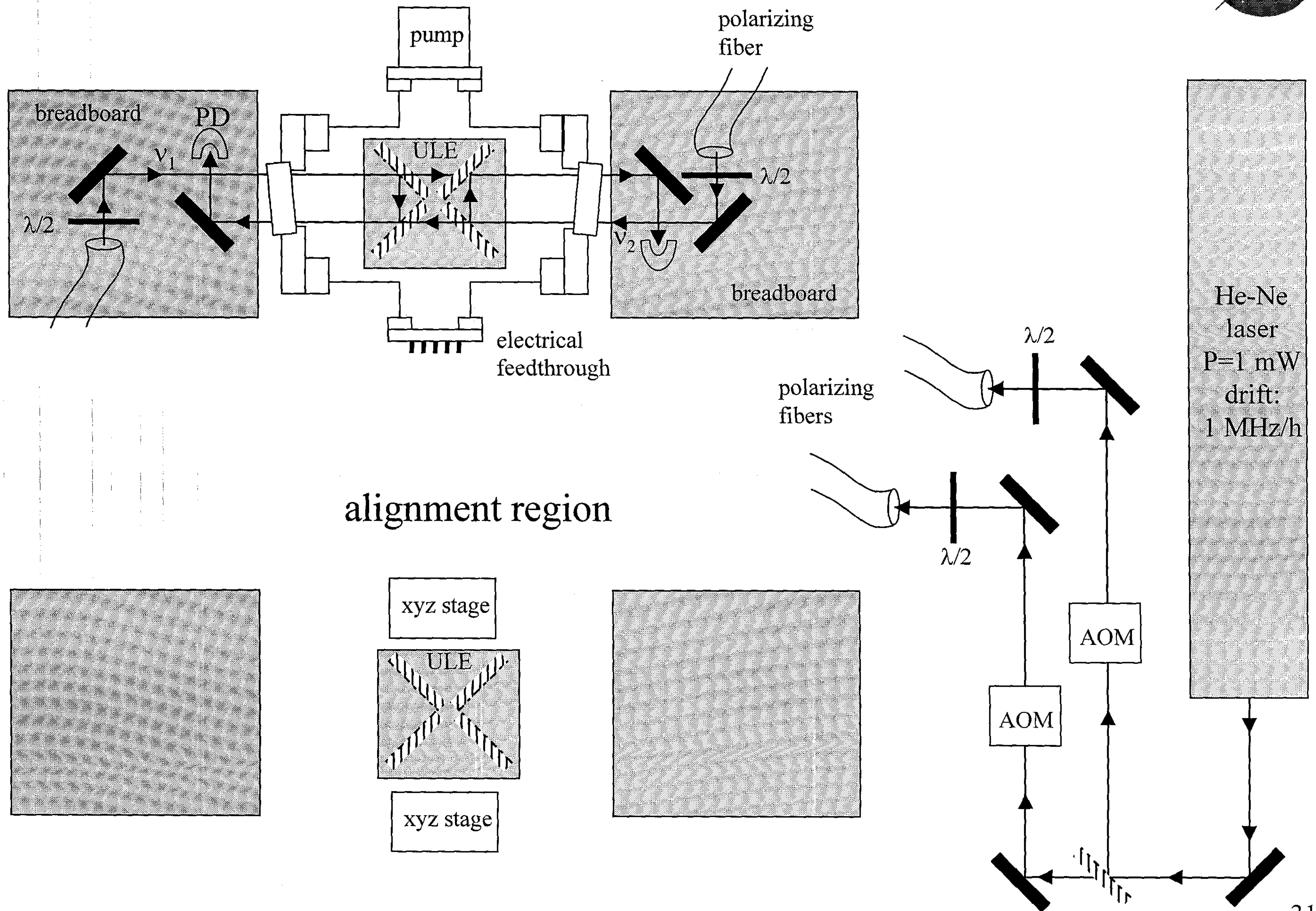


Vacuum chamber for interferometer

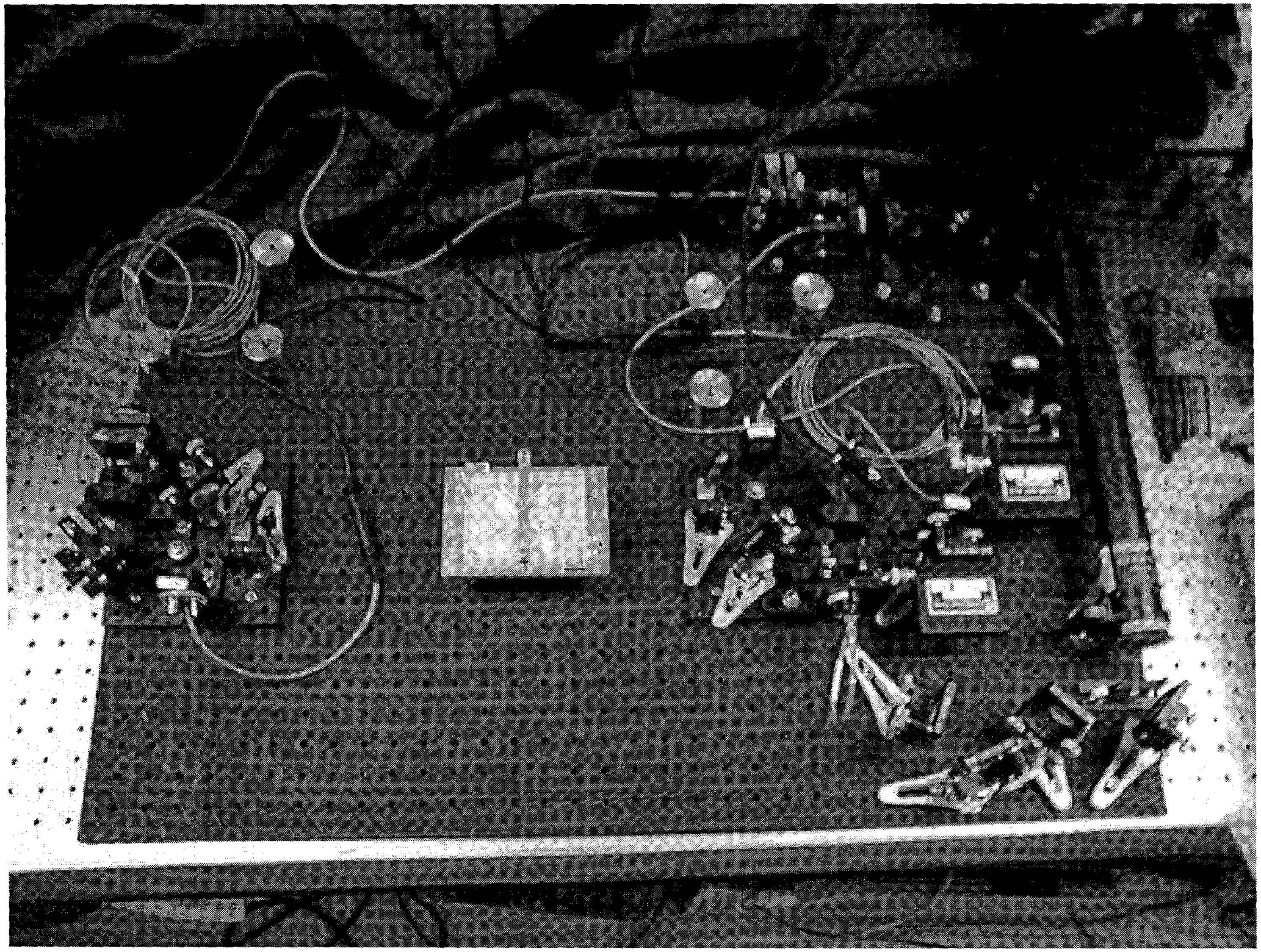




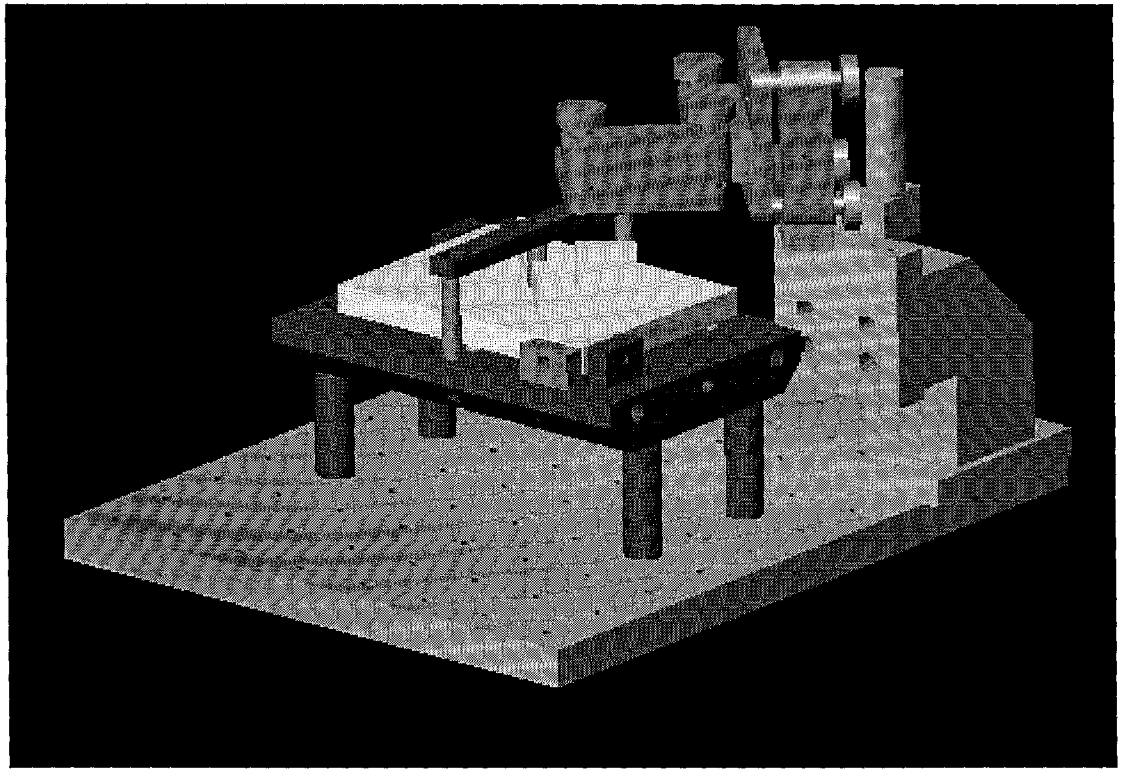
Interferometer breadboard



Interferometer breadboard



Interferometer alignment



Conclusions

EX-5 laser development:

- Surveyed laser systems for best candidates for space applications
- Constructed laser systems at 1064 nm and 778 nm
- Frequency-doubled from 1064 nm to 532 nm
- Observed atomic resonances in iodine and rubidium
- Designed and assembled vacuum systems for Fabry-Pérot cavities
- Designed and fabricated cavity components for 532 nm, 1064 nm, and 778 nm
- Completed design and construction of cavity-lock servo
- Assembled two cavities for 532 nm, evacuated, and tested

LISA metrology:

- Designed and assembled optical system for measuring bonding stability
- Developed a detailed assembly procedure for the interferometer platform
- Designed and fabricated mounts for the platform assembly

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Looking Forward

NASA

EX-5 laser development:

- Complete the optimization of servo gains for cavity lock
- Finish assembling input optics for 2nd cavity system
- Measure short-term stability of Fabry-Pérot cavities
- Assemble and test servo for iodine/rubidium lock
- Measure long-term stability of hybrid laser stabilization system

LISA metrology:

- Assemble interferometer using optical contacting
- Verify performance of phase measurement system
- Assemble interferometer using silicate bonding
- Determine mechanical stability of silicate bonds
- Test interferometers with more exotic optics, e.g., polarizing beamsplitters
- Use system as a testbed for laser phaselocking measurements